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6. AUTHOR(S) J. Baillieul, P.S. Krishnaprasad, R. W. Brockett, P.R. Kumar				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Department of Aerospace and Mechanical Engineering 110 Cummington Street Boston University Boston, MA 02215			8. PERFORMING ORGANIZATION REPORT NUMBER	
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13. ABSTRACT (Maximum 200 words)  This report describes research conducted over a twelve month period under support from a multi-university research grant whose focus is the technological foundations of Communicating Networked Control Systems. Coordinated efforts at four participating institutions are reported here, and in summary form, highlights of each team member's work are reported together with a discussion of interrelationships among the different efforts. The combined work of the participating institutions has led to significant progress in (i) the control theory and applications of feedback systems involving rate-limited communications channels, (ii) the allocation of bandwidth and other resources in networked control systems, (iii) ad hoc optical communications networks, (iv) the geometric foundations and information processing requirements for controlled motions of fleets of UAV's, and (v) scheduling and routing policies for networked control systems which will guarantee stable operation. By maintaining good communication among the various teams, the multi-university center for Communicating Networked Control Systems has made a conscious effort to have each team's efforts support and complement those of the other teams. Specific collaborations among team members will be described, and the report will summarize several ongoing interactions with DoD laboratory personnel.				
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## **Forward**

### **1. Final Report Executive Summary**

This report describes the research conducted under a multi-university research effort to develop the technological foundations of Communicating Networked Control Systems during the period May 1, 2001 – December 31, 2006. At Boston University, the lead institution, progress is reported on five interrelated tasks: (i) new results on source coding of feedback signals in control applications involving rate-limited communications channels have extended to multidimensional systems--- directly extending our previous and also establishing connections between regular quantization and classical control performance metrics; (ii) new results have been reported on distributed control of multiagent systems using constrained sensor feedback; (iii) the team has developed a distributed multi-agent form of actor-critic algorithms for solving Markov decision problems and used this framework to design algorithms for allowing a group of communicating robots to find advantageous paths through hostile terrain; (iv) the team has developed a new approach to route delay-sensitive messages through wireless sensor networks; (v) the team's most recent work on risk associated with changes in data if optimization problem has been reported; (vi) work has continued on robust linear programming (LP); and (vii) work has continued on prototype ad hoc optical communications technologies, this year emphasizing use of retro-reflectors for semi-passive communications. At the University of Maryland, effective approaches to modeling, analysis, control law design, and sensory processing have been developed to create controllers for complex interacting systems such as unmanned aerial/ground vehicles operating autonomously in coherent groups/formations. Progress in the setting of small networks of vehicles has been substantial. However scaling such approaches to large groups in a principled manner is a major challenge. In this work, the introduction of geometric methods, both in understanding the formation control problem and in treating DOD-relevant sensory processing problems, such as those based on acoustics, is suggesting ways to overcome the barrier of scaling up. Our specific approaches also include: (a) the use of motion control languages such as MDLe for tokenizing control laws, and hence finitizing, control and communication design questions; (b) investigation and exploitation of biological paradigms. Work at Harvard has shown that problems with constraints on the feedback information available can be formulated as problems involving the control of an associated Liouville equation. A number of concrete problems of this type have been solved, giving rise to controls which are optimal in the sense that implementation cost and trajectory optimality have been considered jointly. This seems to be the first successful formulation of problems of this type. The Harvard group has also applied the principles of automatic control to the design of queuing protocols. In his paper cited above Adaska has shown that the popular fluid models for queuing systems can be controlled so as to avoid some of the peak load problems that the usual protocols are plagued by. In a third area, the group has continued the investigation of the relationship between analog and digital implementation of information processing systems. This has focused on the operation of pulse-like systems and their relationship to conservative Hamiltonian systems. The role of conserved quantities in information processing has been noted before and this is now being woven into a set of results in which energy efficiency also plays a role. The University of Illinois effort obtained sharper path loss exponents under which the scaling law of transport capacity in wireless networks can be characterized. They have also developed and analyzed a distributed asynchronous protocol for clock synchronization in wireless networks. They have also implemented it, and shown its comparative superior performance with respect to a leading protocol. They have shown how a straightforward adaptation of a price-feedback based algorithm for TCP can lead to the desired fair equilibrium being unstable in wireless networks, and also how spurious equilibria are created. We have developed a multi-channel MAC protocol that can exploit fading diversity at the same time scale as medium access. The team has developed and implemented an algorithm for object tracking by directional sensors in a sensor network.



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## 4. Statement of the Problem Studied

There has been an explosive growth in various forms of communication networks of the last decade, fueled mainly by the availability of small, low cost, and low power digital electronics---enabled by sophisticated algorithms for coding, modulation, and power control. At the same time, there has been a less visible but still dramatic increase in the incorporation of digital electronics in the control systems encountered throughout contemporary technology---automotive applications providing a significant example. Because of technical problems centering on standards, cost, security, and reliability, and because of the rapidly changing nature of these fields, there had been very little cross fertilization between control and communication technologies when this project was proposed in 2000. The possibilities for additional functionality inherent in merging these technologies appeared to more than justify the five-year research effort that is the subject of this final report. While the report's emphasis is specifically on the research that was supported under the subject grant, it also describes some related work that has been undertaken by other groups who also realized the importance of the area.

## 5. Summary of the Most Important Results

In the Boston University component of the research effort, progress is reported in five areas. In the first of these, new results on source coding of feedback signals in control applications involving data-rate constrained communications channels have been extended from the scalar case to the multidimensional case. Our previous work reported results on coding strategies for scalar feedback systems with data-rate-limited feedback channels in which the data-rate constraints are time varying. Such rate-varying channels are typically encountered in communications networks in which links between nodes are subject to noise, congestion, and intermittent disruption. The group has continued to work on source coding methods for feedback control which will work near that data rate limit but which are also robust with respect to changes in achievable data rates (i.e. changes in the capacity of the feedback channel). The effort has led to several papers which extend the results appearing in the Sept. 2004 issue of the *IEEE Transactions on Automatic Control* to the multidimensional case. Several rather distinct approaches have been followed. In one, a novel control coding scheme has been presented, and in terms of this, it has been shown that the advantages of coarse signal quantization that had earlier been reported for scalar systems remain in the multidimensional case. The key is to allocate the communication bandwidth efficiently among faster and slower modes. There is introduced a technique that allocates bandwidth by assigning time slots. The merit of this technique can be discussed in terms of its robustness with respect to time-varying communications bandwidth constraints and also in terms of how well it operates when the feedback channel capacity is near the theoretical minimum data rate. A completely different approach has been to examine quantization strategies based on classical feedback control designs. What is emerging is an understanding that there is a tradeoff between using classical design methods (with the simplicity and optimality that goes along with these) and designs which are tailored to make the most efficient use of the channel.

Work reported during the past year on nonlinear control using low data-rate feedback information has been focused on aspects of geometric nonlinear control theory that have proven to be useful in applications such as the (kinematic) control of formations of robot vehicles. There are many special features and challenges in the design and analysis of feedback control laws for systems arising in nonholonomic mechanics (such as wheeled robot vehicles, autonomous air and underwater vehicles,



etc.), and these challenges need to be revisited in the context of problems where the available feedback signals must be channeled through noisy and intermittent links in a wireless communications network. While a large body of technical literature has been published over the past five years concerning the fundamental relationship between time constants of linear control systems and the data-rates that are required to achieve basic control objectives (e.g. stable operation), much remains to be understood. For nonlinear control systems, even rudimentary questions regarding communications rate constraints on feedback links remain to be answered. During the past year, our published research has also emphasized *network coding* strategies for effectively using feedback from distributed sensors. A number of researchers have recently begun to look at the problem constraints on feedback channel capacity in decentralized feedback control structures. In our own work, we examine the way in which decentralization magnifies the degradation of information due to noise and asynchronism among decentralized sensors and leads to instabilities even in cases where feedback channels have ample capacity for stable operation of a system with centralized components. Further, we have proposed an approach to solving the observed problem by a novel source-coding strategy which is similar to but different from the well known Gray code.

The Boston University team has conducted research on theory and applications of decentralized control of multiple mobile agent systems. We have developed a simple decentralized control law which stabilizes rigid formations of point robots in a way that is consistent with recent work B.D.O. Anderson and a number of others. The feedback law is simple in that it is shown to make parsimonious use of feedback information in a precise sense, and it is also simple in that it is the obvious one would try to control the relative positions of a group of robots. The law is exponentially complex, however, in the sense that the number of stable equilibria grows exponentially as a function of the number of point robots involved in the formation. Assuming only one formation of the exponentially many possibilities is of interest, we have addressed the problem of achieving the desired formation using the feedback law. We have preliminary results on the combinatorial problem of determining all possible formation topologies as well as the critical point theory of the proposed control law.

The grant supported an initiation of the study of risk and reliability in the context of wirelessly communicating networks of sensors, actuators, mobile agents, etc.

ASPECT 1: While classical models of risk in insurance and financial markets have been effectively treated by the methods of stochastic and adaptive processes, we have begun research based on the premise that a wide variety of new technologies will require qualitatively different methods which emphasize risk due to constraints on spatial and temporal distribution of information, risk due to scale, and risk due to extreme sensitivity to changes in operating conditions. Our ongoing research explores elements of risk in complex dynamical systems which arise from sensitivity to operating conditions. It is argued that complexity based risk of this type is an essential part of what makes competitive athletics interesting. To explore this proposition, a simple interval mapping game has been proposed and studied. Analysis of the game dynamics shows that complexity based risk cannot be completely eliminated although it is possible to plan play strategies to manage it.

ASPECT 2: We have also studied time-invariant, memorylessly quantized control of scalar plants over error-prone binary channels. As bit errors cannot be compensated for, plant stability is impossible. Thus, the simplest feasible objective is to ensure that the closed-loop is in some sense well-behaved for as long as possible. We have proposed a definition of time-to-failure for such systems, using the notion of conditional worst- and best-case states. It has been shown that the stochastic evolution of an auxiliary system can be exactly characterized by a finite-state Markov



chain. With this approach, explicit expressions for the time-to-failure distribution can be derived for a range of non-trivial parameter values. The current research is focused on considering performance trade-offs when the total transmission power and control power are finite.

Also, at B.U. we have conducted research on the use of multimodal mobile sensing to map spatially varying intensities of physical quantities (temperature, light, sound levels, chemical density, etc.) in unknown domains. Provably stable control laws have been developed and implemented on an actual robotic system. Current research is focused extending single agent results to decentralized multi agent cooperative systems.

Actor-critic algorithms – an approximate dynamic programming methodology for solving Markov decision problems (MDPs) – adopt a randomized class of policies with a specific structure incorporating the designer’s intuition about key features of the state-control space that should affect the control actions. The class of policies adopted is parametrized by a (typically low-dimensional) parameter vector  $\Theta$  and the actor-critic algorithm optimizes policy performance with respect to  $\Theta$  by using a simulation of the MDP. To that end, the algorithm combines exploration of the state-control space with descent along the performance gradient with respect to  $\Theta$ . We developed a distributed multi-agent form of actor-critic algorithms. Our algorithm allows us to use multiple agents to simultaneously explore the state-control space. Each agent maintains its own  $\Theta$  and updates it based on local information and information received from a subset of other agents (e.g., the ones within a certain communication range). Under suitable conditions, we show that all agents reach consensus and converge to the optimal  $\Theta$ .

We applied our algorithm to the problem of navigating a group of communicating robots through a hostile terrain. Specifically, the robots move on a two-dimensional grid and seek a route from a given origin to a given destination. The terrain is littered with “hotspots” they want to avoid. Passing from the vicinity of hotspots incurs high cost and the robots’ objective is to find the minimum cost path. The robots do not know the various route costs in advance; they only have some rough information about the location of the hotspots and their relative severity (e.g., from satellite imagery). Hence, a centralized approach where one has global and full cost information in advance and solves a shortest path problem is not applicable. Our algorithm converges to a close-to-optimal path and much faster than the single-agent version. Our results illustrate the trade-off between the speed of convergence and the communication radius of the robots.

We have also considered wireless sensor networks with nodes switching “ON” (awake) and “OFF” (sleeping) to preserve energy, and transmitting data over channels with varying quality. The objective is to determine the best path from each node to a single gateway. Performance metrics of interest are: the expected energy consumption for transmissions and the probability that the latency exceeds a certain threshold. Under Markovian assumptions on the sleeping schedules and the channel conditions, we obtain the expected energy consumption of transmitting a packet on any path to the gateway. We also provide an upper (Chernoff) bound and a tight large deviations asymptotic for the latency probability on each path. To capture the trade-off between energy consumption and latency probability we formulate the problem of choosing a path to minimize a weighted sum of the expected energy consumption and the exponent of the latency probability. We provide two algorithms to solve this problem: a centralized stochastic global optimization algorithm and a distributed algorithm based on simulated annealing.

## **Location and Localization Problems in Networked Control Systems**



An overarching problem in systems of networked devices that are connected by freespace optical or RF links, is the problem of localization and location determination. Center researchers made progress toward solving both problems. Members of the research team have developed a robust localization system allowing Wireless Sensor Networks (WSNETs) to determine the physical location of their nodes. Under this approach, the coverage area is split into partitions and the system seeks to identify the partition where a sensor resides based on observations made by stationary sensors (clusterheads). These observations are assumed random and are often RF-characteristics of the signal transmitted by the sensor and received by the clusterheads. To every partition-clusterhead pair there is associated a family of probability density functions (pdfs) from which observations are assumed to be drawn and pose the localization problem as a composite multi-hypothesis testing problem. We establish conditions under which the Generalized Likelihood Ratio Test (GLRT) is optimal in a Generalized Neyman-Pearson (GNP) sense. We have obtained the optimal GLRT threshold to minimize the maximum probability of error and establish a probabilistic performance guarantee for the resulting decision rule. We have also studied the problem of optimally placing clusterheads to minimize the maximum probability of error and establish a performance guarantee for the optimal placement. It was demonstrated how the localization system can be implemented in a distributed manner by appropriate in-network processing. The proposed approach continues to be validated in an experimental testbed.

A related component of the research at Boston University is aimed at exploring *ad hoc freespace optical networks* technologies. Some of the early work – described in previous interim progress reports, involved the use of mobile robots to establish and maintain line-of-sight communication links between advanced (Canobeam) freespace optical communication transceivers. The main idea was to deploy a squadron of mobile robots with steerable mirrors that could be used to find and redirect laser beams. This system had the advantage over most commercially available systems in which fixed transceivers must be carefully aligned to assure good signal reception. The technology needed to dynamically reconfigure freespace optical communication networks required the solution of several interrelated problems:



**Figure:** artoo.bu.edu is configured with IR beam detectors and a gimbaled mirror system for research on freespace optical communications. Artoo is one of several mobile robots dedicated to research in the Center for Communicating Networked Control Systems.

1. The beam location problem;
2. The beam pointing problem;
3. The beam tracking problem; and
4. The cooperative signal maintenance problem.

The *beam location problem* involves searching a 2-dimensional space to locate the laser beam of one of the optical communications transceivers. Each transmitted beam must be located by one of the mobile robots in the group. The *beam pointing problem* requires the robot agents which have found the communication beams from the optical transceivers to find each other and direct the laser beams so as to form a reliable communications channel from one transceiver to the other. The *beam tracking problem* involves motion of the robot agents in which the communications channel is maintained. This is an important problem which anticipates the objective of stabilized mobile freespace optical communications which will be a large part of future phases of the research. A related problem is that of *cooperative signal maintenance*. Work on this problem is aimed at understanding the types of *side information* the robot agents require to most effectively carry out the mission of maintaining a reliable information link.

In a related effort, the Boston University team has worked on ad hoc free-space optical communication. We have reported preliminary work on a prototype semi-passive system, the main



hardware component of which is a MEMS-based spatial light modulator (SLM) integrated with a retroreflector to produce an inexpensive and lightweight device which is capable of reliably modulating a laser beam probe and reflecting it to its place of origin. Future research on such systems is aimed at developing the underlying control principles needed to create reliable ad hoc optical communications networks based on such SLM-modulated retro-reflectors together with appropriate pointing and tracking technologies.

The ad-hoc point-to-point communication effort led to significant new architectures, technologies, and prototype systems of immediate value to the Army. A new class of MEMS mirror modulator was developed in this MURI project. The device is comprised of a thin, tensile gold-coated silicon nitride membrane supported by a regular array of glass attachments to a flat, rigid silicon substrate. This mirror modulator is designed to be optically flat in its unpowered state, and becomes optically diffractive in its powered state. Efficient, low-power electrostatic actuation is used to modulate the device using a one-bit, one line controller signal. Fabrication techniques were selected to make the device extraordinarily inexpensive in comparison to exiting MEMS optical mirrors. The result is a device that can modulate light with high contrast ( $>5:1$ ) at frequencies of up to 200kHz, in a package weighing less than 20gm and consuming no more than 500mW at maximum data rate, producible for less than \$50. This device was subsequently incorporated into a retroreflector using a single aspheric lens, forming a compact, low-power optical transponder (Secure Communicating Optical Transponder, or SCOUT). Supported by ARL Cooperative Agreement funding, the Scout combines a MEMS modulated transponder with existing weapon aiming technology to provide new capabilities to the warfighter.

In recent work at the University of Illinois, networks with multiple source-destination pairs, involving possibly multicast, and where there are multiple nodes that can serve as potential relay nodes, have been considered. A multi-source multi-relay coding scheme has been developed. In this scheme, each source's information is sent to its destination nodes via a multi-relay route, with the multiple multi-relay routes operating concurrently even when they intersect with each other, in the same spirit as code-division multiple-access (CDMA). It has been shown that in the generalization to multiple sources, backward decoding achieves higher rates than sliding-window decoding. In particular, the exact capacity for the data downloading problem in sensor networks, where there are multiple sensor sources and one sink or collector node, is established for certain geometries when there is phase fading that is unknown to the transmitter.

In joint work, E.W. Justh and P.S. Krishnaprasad have been investigating coordination of small formations of UAVs (unmanned aerial vehicles). A distinctive feature of the approach taken in this work is that the focus is on steering laws or control laws that determine the curvature of a UAV trajectory. The suitability of such laws is based on the accomplishment of goals such as formation cohesion, point-to-point transfer, stabilization of prescribed formation shapes and formation re-shaping. The constraints/requirements on UAV-to-UAV communication were investigated. Ultra wide band (UWB) communication was considered for obtaining range and bearing. In a test-bed developed in the Intelligent Servosystems laboratory, work on planar problems is centered on exploration of real-time control over Bluetooth radio links and use of state-of-the-art inertial sensing, and location sensing using a network of ultrasonic beacons. Initial work on planar problems has been extended to include continua of interacting particles – an approach to obtaining qualitative and quantitative results on swarms of UAVs. A geometric approach based on Frenet-Serret equations in the plane has been extended to three dimensions. Here alternative frames for curves, *the relatively parallel adapted frames*, proved to be most appropriate. These frames are effective even in the absence of certain smoothness properties or non-degeneracy properties of trajectories. Lyapunov functions have been used to derive and prove convergence results for control laws that support a variety of formation behaviors. More recently, the methodology of interacting particles on Lie



groups was extended to explore problems of conflict (e.g. steering tactical munitions to target) and this established contact with newer questions and ideas from biology, specifically the concept of motion camouflage. Here the convergence analysis techniques took into account singularities associated with collision states. This work appeared in the Proceedings of the Royal Society of London (series A) in 2006. An extension to 3D appeared in the Proceedings of the IEEE Conference on Decision and Control in December 2006. Collaboration with biologists has strongly informed our work on the optimality questions associated with predator-prey pursuit laws. The problem of an echolocating bat hunting insect prey in the dark has been a source of insight. This work was published in the Public Library of Science (Biology) in 2006.

Demonstrations have been carried out with small number of ground vehicles (fewer than 5) and the implementation of the feedback control laws has been done in a style reminiscent of our work on motion description languages (MDLe), during summer 2003 and fall 2003. During spring 2005 significant experimental work was initiated to fully utilize MDLe within a new laboratory test-bed. A new networked localization system called Cricket was set up in the laboratory to support cooperative control of mobile robots. This system utilizes ultrasonic and RF pulses to serve as an “indoor GPS” with a precision of a few centimeters. Work with two undergraduates (Young and Kushleyev) led to a complete demonstration of the system with robots for the first time, during summer 2005. It was then demonstrated in an air vehicle setting, specifically a hovercraft, as part of the M.S. thesis of Zachary Kulis. During summer 2006, a group of undergraduates (Hosam Haggag, Golbarg Mehraei and Joshua Lioi) developed demonstrations of pursuit type control laws using Cricket in the feedback loop. This work shows that Cricket type “acoustic GPS” techniques for indoor localization can be very useful in robot rendezvous tasks. In the fall of 2006, this work was extended to somewhat unstructured settings outside the laboratory with a view to combining conventional GPS with indoor GPS based on Cricket technology. Three undergraduate students, John Karvounis, Travis Young and Ermin Wei are participating in this task. The integration with conventional GPS is expected to be completed in May 2007. Graduate student Kevin Galloway is leading the team. Undergraduate student Thomas Capon is completing a project to upgrade the hovercraft control system to Zigbee wireless communication technology and fully on-board control.

Collaboration with former graduate student Dr. Fumin Zhang (now post-doctoral research associate at Princeton) is continuing to develop obstacle avoidance algorithms using ideas similar to those in the UAV formation control work. New boundary following control laws have been devised, and tested on ground vehicles. (This work is leading to transfer of methodologies and algorithms to a project on underwater glider control for marine sampling at Princeton University, funded by Office of Naval Research.)

In the joint work of Arash Komaee, P. S. Krishnaprasad and Prakash Narayan, closed loop control for optical links using point process detection models and nonlinear filters has been developed. This work is expected to be useful in applications involving line-of-sight optical links for coordination of groups of ground and aerial vehicles. The work has been submitted for publication.

Work of Bijan Afsari (Ph.D. student in Applied Mathematics) has led to new fast algorithms for solving problems of separation of mixed acoustic signals. He has presented some of his new work in ICA 2006 in March 2006, and is presenting more recent work at the ICASSP meeting in April 2007.

New significant collaborations involving biologists and leveraged support from NIH-NIBIB and AFOSR has been initiated during the course of our research. These collaborations have influenced our approach to interacting systems in conflict. The specific inspiration from biology arises from the study of bat echolocation to hunt prey.



During the summer of 2006, Dr. Eric Justh resigned his position as Assistant Research Scientist at the University of Maryland and joined the permanent technical staff of the Naval Research Laboratory (NRL). Collaborations with him continue on a regular basis without interruption, despite this change. He supervised the work of Kevin Galloway at NRL on estimation problems arising in formation flight. Kevin is a full time Ph.D. student at the University of Maryland.



## 6. List of Publications and Technical Reports

### Boston University

- 1.J. Baillieul, “Bi-Directional Electrostatic Actuator Operated with Charge Control,” *Proceedings of the 2002 Joint Electrostatics Society of America/Institute of Electrostatics Japan Annual Conference*, June 25-28, 2002, Northwestern University, Evanston, IL (with T. Sugimoto, M. Horenstein, and K. Nonaka).
- 2.J. Baillieul, “Feedback Designs in Information-based Control,” *Stochastic Theory and Control – Proceedings of Workshop held at the University of Kansas*, Bozenna Pasik-Duncan (Ed.), Lecture Notes in Control and Information Sciences, Springer-Verlag, New York, 2002, pp. 35-57.
- 3.J. Baillieul, “Feedback Coding for Information-Based Control – Operating Near the Data-Rate Limit,” in the *Proceedings of the 2002 IEEE Conference on Decision and Control*, Las Vegas, NV, December, 2002, pp. 3229-3236.
- 4.J. Baillieul and A. Suri, “Information Patterns and Hedging Brockett’s Theorem in Controlling Vehicle Formations,” in the 2003 *IEEE Conference on Decision and Control*, Maui, Hawaii, December, 2003, TuMO2-6, pp. 556-563. Preprint available: <http://people.bu.edu/johnb/CDC03.1.pdf>.
5. K. Li and J. Baillieul, “Robust Quantization for Digital Finite Communication Bandwidth (DFCB) Control,” 2003 *IEEE Conference on Decision and Control*, Maui, Hawaii, December, 2003, ThAO2-1, pp. 3130-3135. Preprint available: <http://people.bu.edu/johnb/CDC03.2.pdf>.
6. A.C. Smith and J. Baillieul, “Vortex Models for the Control of Stall,” 2003 *IEEE Conference on Decision and Control*, Maui, Hawaii, December, 2003, WeM12-5, pp. 2407-2412. Preprint available: <http://people.bu.edu/johnb/CDC03.3.pdf>.
7. J. Baillieul, “Control Methods for Very Small-scale Devices,” in *Proc. Of the 2003 Soc. For Experimental Mechanics Annual Conf. And Exposition*, Charlotte, NC, June-2-4, 2003. pp. 111-116
8. J. Baillieul, “Intelligent Nonlinear Control,” in the *Proceedings of the 22-nd Chinese Control Conference*, August 11-13, 2003, Three Gorges University, Ychang, P.R. China, p. 1.
9. J. Baillieul, “Data-rate Problems in Feedback Stabilization of Drift-free Nonlinear Control Systems,” in *Proceedings of the 2004 Symposium on the Mathematical Theory of Networks and Systems (MTNS)*, Katholieke Universiteit Leuven, Belgium, July 5-9, 2004, Tue., 7/6, 11:10-11:50, 5 pp.
10. K. Li and J. Baillieul, “Robust Quantization for Digital Finite Communication Bandwidth (DFCB) Control,” *IEEE Transactions on Automatic Control*, Special Issue on Networked Control Systems, V. 49:9, September, 2004, pp. 1573-1584.



11. K. Li and J. Baillieul, "Control with Time-Varying Feedback Communication Constraints – The Case of Dimension Greater Than One," in *Proceeding of the 5<sup>th</sup> Asian Control Conference*, July 20-23 2004, Melbourne, Australia, pp. 1906-1914.
12. K. Li and J. Baillieul, "Data-Rate Requirements for Nonlinear Feedback Control," to appear in *Proceedings of the 6<sup>th</sup> IFAC Symposium on Nonlinear Control Systems (NOLCOS 2004)*, Stuttgart, Germany, September 1-3, 2004, pp. 1277-1282.
13. K. Li and J. Baillieul, "Robust Quantization and Coding for Multidimensional Linear Systems under Data Rate Constraints," *43-rd IEEE Conference on Decision and Control*, The Bahamas, December, 2004, WeB03.2, pp. 1920-1925.
14. K. Nonaka, T. Sugimoto, J. Baillieul and M. Horenstein, "Bi-directional Extension of the Travel Range of Electrostatic Actuators by Open Loop Periodically Switched Oscillatory Control," *43-rd IEEE Conference on Decision and Control*, The Bahamas, December, 2004, WeB04.5, pp. 1964-1969.
15. J. Baillieul, "The Geometry of Sensor Information Utilization in Nonlinear Feedback Control of Vehicle Formations," in *Cooperative Control: A Post-Workshop Volume 2003 Block Island Workshop on Cooperative Control*, June 10-11, 2003, V. Kumar, N.E. Leonard & A.S. Morse, Eds. Lecture Notes in Control and Information Sciences, Volume 309, Springer-Verlag, New York, ISBN: 3-540-22861-6.
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  95. K. Manousakis, J. S. Baras, "Improving the Speed of Dynamic Cluster Formation in Manet via Simulated Annealing ", Proceedings of the 24<sup>th</sup> Army Science Conference (ASC2004), Orlando, Florida, November 29 – December 2, 2004.
  96. J.S. Baras, X. Tan, "Control of Autonomous Swarms Using Gibbs Sampling", Proceedings of the 43<sup>rd</sup> IEEE Conference on Decision and Control (CDC'04), pp. 4752-4757, Atlantis, Paradise Island, Bahamas, December 14-17, 2004.
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98. M. Rabi, J.S. Baras, "Sampling of Diffusion Processes for Real-time Estimation", Proceedings of the 43<sup>rd</sup> IEEE Conference on Decision and Control (CDC'04), pp. 4163-4168, Atlantis, Paradise Island, Bahamas, December 14-17, 2004.
99. W. Xi, X. Tan, J.S. Baras, "A Hybrid Scheme for Distributed Control of Autonomous Swarms", Proceedings of the ACC05, pp. 3486-3491, Portland, Oregon, June 8-20, 2005.
100. K. Manousakis, J.S. Baras, "Mobility Based Distributed Domain Generation Algorithm for MANETs", Proceedings of WIRELESS 2005, pp. 820-825, Maui, Hawaii, June 13-16, 2005.
101. W. Xi, X. Tan, J.S. Baras, "Gibbs Sampler-based Path Planning for Autonomous Vehicles: Convergence Analysis", Proceedings of 16<sup>th</sup> IFAC World Congress, Prague, Czech Republic, July 4-8, 2005.
102. K. Chandrashekar, R. Morera, A. McAuley, and J. S. Baras, "Domain Based Hierarchical Routing for Large Heterogeneous Manets", Military Communications Conference, 2005 – MILCOM 2005 (IEEE), pp. 1284-1290, Vol. 2, Atlantic City, NJ, October 17-20, 2005.
103. K. Manousakis and J. S. Baras, "Design Framework for Hierarchy Maintenance Algorithms in Mobile Ad Hoc Networks", Proceedings of Military Communications Conference (MILCOM 2005), pp. 2506-2511, Vol. 4, Atlantic, City, NJ, October 17-20, 2005.
104. W. Xi, X. Tan, J. Baras, "A Stochastic Algorithm for Self-Organization of Autonomous Swarms", 44<sup>th</sup> IEEE Conference on Decision and Control and European Control Conference ECC 2005, pp. 765-770, Seville, Spain, December 12-15, 2005.
105. J. Baras and M. Rabi, "Maximum Entropy Models, Dynamic Games, and robust Output Feedback Control for Automata", 44<sup>th</sup> IEEE Conference on Decision and Control and European Control Conference ECC 2005, pp. 1043-1049, Seville, Spain, December 12-15, 2005.
106. P. Hovareshti and John S. Baras, "Consensus Problems on Small World Graphs: A Structural Study", 2006 International Conference on Complex Systems, Boston, MA, May 28-31, 2006.
107. W. Xi and J. S. Baras, "Distributed Control of Autonomous Swarms by Using Parallel Simulated Annealing Algorithm", Proceedings of the 14th Mediterranean Conference on Control and Automation, Ancona, Italy, June 28-30, 2006.



108. M. Rabi, G. Moustakides and J. S. Baras, "Efficient Sampling for Keeping Track of an Ornstein-Uhlenbeck Process", Proceedings of the 14<sup>th</sup> Mediterranean Conference on Control and Automation, Ancona, Italy, June 28-30, 2006.
109. M. Rabi, J. S. Baras, and G. Moustakides, "Multiple Sampling for Estimation on a Finite Horizon", Proceedings of the 45<sup>th</sup> IEEE Conference on Decision and Control (CDC'06), pg. 1351-1357, San Diego, CA, December 13-15, 2006.
110. W. Xi and J. S. Baras, "Gibbs Sampler Based Control of Autonomous Vehicle Swarms in the Presence of Sensor Errors", Proceedings of the 45<sup>th</sup> IEEE Conference on Decision and Control (CDC06), San Diego, CA, December 13-15, 2006.
111. J. Baras, "Maximum Entropy Models, Dynamic Games and Robust Output Feedback Control of Nonlinear Systems", Proceedings of the 45<sup>th</sup> IEEE Conference on Decision and Control (CDC'06), San Diego, CA, December 15, 2006.
112. Pedram Hovareshti, Vijay Gupta and John Baras, "Sensor Scheduling using Smart Sensors," submitted to 2007 IEEE Decision and Control Conference.
113. Vijay Gupta , Nuno C. Martins and John S. Baras, "Observing a Linear Process over Packet Erasure Channels using Multiple Sensors: Necessary and Sufficient Conditions for Mean-square Stability," submitted to 2007 IEEE Decision and Control Conference.
114. Maben Rabi, George V. Moustakides and John S. Baras, "Average Cost Repeated Sampling for Filtering," submitted to 2007 IEEE Decision and Control Conference.
115. Punyaslok Purkayastha and John S. Baras, "Convergence Results for Ant Routing Algorithms via Stochastic Approximation and Optimization," submitted to 2007 IEEE Decision and Control Conference.
116. Maben Rabi and John S. Baras, "Level-triggered Control of a Scalar Linear System," submitted to 2007 Mediterranean Control Conference.
117. Wei Xi and John S. Baras, "MPC Based Motion Control of Car-like Vehicle Swarms," submitted to 2007 Mediterranean Control Conference.

### **Invited Lectures by Center Principals**



J. Baillieul, ``Risk Engineering and the Design of Reliable Networked Control Systems,’’ colloquium talk at the Division of Control and Instrumentation, EEE, Nanyang Technological University, September 2, 2005.

J. Baillieul, ``Risk Engineering and the Design of Reliable Networked Control Systems,’’ delivered at the RECSYS Workshop on Networked Embedded Systems, EPFL, Lausanne, Switzerland, December 5, 2005.

J. Baillieul, ``Source Coding for Guaranteed Performance of Control Systems with Time-Varying Feedback Channel Capacity,’’ Colloquium Lecture, Dept. of Information Engineering, Univ. di Padova, Padova, IT, December 7, 2005.

J. Baillieul, “Structured and Stochastic Rules for Motions of Groups of Robotic Agents,” Hour lecture at the workshop entitled “Swarming by Nature and by Design,” Feb. 27-Mar. 3, 2006 at the Institute for Pure and Applied Mathematics (IPAM), UCLA.

J. Baillieul, ``Source Coding for Guaranteed Performance of Control Systems with Time-Varying Feedback Channel Capacity,’’ CNLS Workshop on Challenges and Opportunities in Distributed Sensor Networks, Los Alamos, March 10, 2006.

J. Baillieul, “Risk-Sensitive Control of Complex Decentralized Systems,” Princeton University Engineering Colloquium Lecture, April 14, 2006.

J. Baillieul, “Structured and Stochastic Rules for Motions of Groups of Robotic Agents,” NSF Workshop: Future Directions in Systems Research for Networked Sensing, Boston University, May 25, 2006 (invited hour lecture).

J. Baillieul, “Source Coding for Guaranteed Performance of Control Systems with Time-Varying Feedback,” Colloquium Lecture, Chinese University of Hong Kong, July 17, 2006.

J. Baillieul, “Rethinking Control Engineering in a Networked World,” Keynote Lecture, 1<sup>st</sup> International Conference on Computer Science & Education, Xiamen University, Xiamen, China, July 27, 2006.

J. Baillieul, “Regular Quantization for Communication-Constrained Feedback Channels,” University of Michigan Combined Control Systems Seminar, October 13, 2006.

I.C. Paschalidis, ``Research Challenges in RFIDs and Sensor Networks’’, Invited Panelist, IDC RFID Update Conference, June 2005, Boston, Massachusetts.

I.C. Paschalidis, ``Localization for Sensor Networks: Accurate or Robust (or both) ?’’, The Sensor Network Consortium, May 2005, Boston, Massachusetts.

I.C. Paschalidis, ``Performance evaluation of Sensor Networks’’, The Sensor Network Consortium, May 2005, Boston, Massachusetts.

I.C. Paschalidis, ``Statistical Location Detection and Optimal Routing in Sensor Networks’’, Invited Talk, General Electric Labs, January 2005, Niskayuna, New York.



I.C. Paschalidis, “Optimization Adventures in the Wonderland of Wireless Sensor Networks”, Invited Lecture, Department of Electrical and Computer Engineering, University of Connecticut, November 2005.

I.C. Paschalidis, “Sensor Networks: Localization, Transmission Scheduling, and Energy-Aware Routing with QoS Guarantees”, Invited, Workshop on Challenges and Opportunities in Distributed Sensor Networks, Center for Nonlinear Studies, Los Alamos National Laboratory, March 9—10, 2006, Los Alamos, New Mexico.

I.C. Paschalidis, “Energy-Aware Sensor Network Routing with QoS Guarantees”, Invited Talk, MITRE Corp., June 2006, Bedford, Massachusetts.

I.C. Paschalidis, “Localization with Sensor Networks and related challenges”, Invited Talk, United Technologies Research Center, October 2006, Hartford, Connecticut.

I.C. Paschalidis, “Systems-level opportunities for much needed efficiency gains in sensor networks”, Invited Talk, ARRM06 Industry & IMEC Review Meeting, October 2006, Leuven, Belgium.

I.C. Paschalidis, “The Center for Information and Systems Engineering and the Sensor Networks Consortium”, Invited Talk, Holst Centre, IMEC Netherlands, October 2006, Eindhoven, Netherlands.

I.C. Paschalidis, “Sensor networks and applications in homeland security”, Invited Talk, Symposium on “UK Technologies for Security” organized by the United Kingdom government, October 30, 2006, UK Consulate, Boston, Massachusetts.

I.C. Paschalidis, “Minimal Energy Routing with Latency QoS Guarantees”, The Sensor Network Consortium, November 2006, Boston, Massachusetts.

I.C. Paschalidis, “Wireless Sensor Networks: A playground for optimization methodologies”, Invited Lecture, Dipartimento di Ingegneria, Università degli Studi del Sannio, Benevento, Italy, September 2006.

I.C. Paschalidis, “Optimization of Wireless Sensor Networks”, Invited Lecture, Department of Mathematical Engineering, Université catholique de Louvain, Louvain-la-Neuve, Belgium, October 2006.

I.C. Paschalidis, “Optimization of Wireless Sensor Networks”, Invited Lecture, Department of Electrical and Computer Engineering, Boston University, Boston, MA, November 2006.

I.C. Paschalidis, “Optimization for Protein-Protein Docking”, Invited Lecture, Operations Research Center, Massachusetts Institute of Technology, November 30, 2006.

I.C. Paschalidis, “Optimization of Wireless Sensor Networks”, Invited Lecture, Athens Information Technology (AIT) Center, March 12, 2007.

PR Kumar, Distinguished Speaker Seminar, Department of Electrical and Computer Engineering, Carnegie Mellon University, March 2, 2006.



PR Kumar, Toyota Distinguished Lecture on the Convergence of Computing, Communication and Control, organized jointly by CEE/ME/ and EECS. University of California, Berkeley, Feb 10, 2006.

PR Kumar, Distinguished Lecturer, Department of Computing Science, University of Alberta, Canada, January 30, 2006.

PR Kumar, Distinguished Lecture, Xerox Corp., October 13, 2005, Rochester, NY.

PS Krishnaprasad, Spatial Patterns in Cooperation and Conflict – Workshop on swarming in natural and engineered systems, Napa, California, August 3-4, 2005. (20 minutes talk).

PS Krishnaprasad, Control, Observation and Feedback – Quantum Control Summer School, Caltech, Pasadena, August 8, 2005. (hour lecture).

PS Krishnaprasad, Control Systems on Lie Groups – Quantum Control Summer School, Caltech, Pasadena, August 10, 2005. (hour lecture).

PS Krishnaprasad, Natural Frames, Interacting Particles and Stealth – Applied Mathematics Colloquium, University of Illinois, Urbana-Champaign, September 19, 2005 (hour lecture).

PS Krishnaprasad, Pursuit Stealth and Cohesion: Lessons from Nature, CDS Seminar, Caltech, Pasadena, February 28, 2006, (hour lecture).

PS Krishnaprasad, Pursuit Stealth and Cohesion: Lessons from Nature, Workshop on Swarms in Nature and by Design, March 3, 2006, (hour lecture).

PS Krishnaprasad, Pursuit Stealth and Cohesion: Lessons from Nature, Electrical Engineering Seminar, Harvard University, March 10, 2006 (hour lecture).

PS Krishnaprasad, Pursuit Stealth and Cohesion: Lessons from Nature, Mathematics Colloquium, North Carolina State University, April 7, 2006, (hour lecture).

## 7. List of all Participating Scientific Personnel

### **Faculty**

1. John Baillieul, Boston University
2. Thomas Bifano, Boston University
3. Ioannis Ch. Paschalidis, Boston University
4. Roger Brockett, Harvard University
5. P.R. Kumar, University of Illinois
6. P.S. Krishnaprasad, University of Maryland
7. Prakash Narayan, University of Maryland
8. D. Hristu-Varsakelis, University of Maryland
9. John S. Baras, University of Maryland
10. E. W. Justh, University of Maryland



## **Visiting Scientists**

University of Illinois – Jan H. van Schuppen

## **Post Doctoral Fellows**

Harvard University

1. Sean Anderson

University of Maryland

1. Handzel, Post Doc.
2. B. Azimi-Sadjadi, Post Doc

## **PhD Students**

Boston University:

1. Keyong Li, Ph.D. candidate, Department of Aerospace/Mechanical Engineering. PhD Topic: Information-based Control of Networked Systems
2. Yong Liu, Ph.D. candidate, Dept. of Manufacturing Eng., Boston University (degree awarded May 2002).
3. Adam C. Smith, Ph.D. candidate, Department of Aerospace/Mechanical Engineering (supported through other means but working on problems related to the project).
4. Jeremy Grace, Ph.D. candidate, Department of Aerospace/Mechanical Engineering (supported through other means but working on problems related to the project), PhD Topic: Search and Surveillance Methods for Groups of Autonomous Vehicles.
5. Grace Kessenich, MS candidate, Department of Aerospace/Mechanical Engineering (supported through other means but working on problems related to the project), Masters Thesis Topic: Distributed Sensing and the Blind Robot Problem.
6. Dimitar Baronov, Ph.D. candidate, Department of Aerospace/Mechanical Engineering, Boston University
7. Lester McCoy, Ph.D. candidate, Department of Aerospace/Mechanical Engineering, Boston University.
8. Chang Su, Ph.D. candidate, Dept. of Manufacturing Eng, Boston University.
9. Jian Shao, Ph.D. candidate, Dept. of Manufacturing Eng., Boston University (supported through other means but working on problems related to the project).
10. Ying Liu, Ph.D. candidate, Dept. of Manufacturing Eng., Boston University (supported through other means but working on problems related to the project).
11. Yimin Yu, Ph.D. candidate, Dept. of Manufacturing Eng., Boston University (supported through other means but working on problems related to the project).
12. Jonghoon Jeong, Ph.D. candidate, Dept. of Manufacturing Eng., Boston University (supported through other means but working on problems related to the project).
13. Wei Lai, Ph.D. candidate, Dept. of Manufacturing Eng., Boston University (supported through other means but working on problems related to the project).
14. James Kang, Ph.D. candidate, Dept. of Manufacturing Eng., Boston University.
15. Saikat Ray, Ph.D. candidate, Dept. of Electrical and Computer Eng., Boston University (supported through other means but working on problems related to the project).



16. Yang Shen, Ph.D. candidate, Dept. of Manufacturing Eng., Boston University.
17. Dong Guo, Ph.D. candidate, Dept. of Manufacturing Eng., Boston University.
18. Xiangdong Song, Ph.D. candidate, Dept. of Manufacturing Eng., Boston University.
19. Ruomin Yu, Ph.D. candidate, Dept. of Manufacturing Eng., Boston University.
20. Yin Chen, Ph.D. candidate, Dept. of Manufacturing Eng., Boston University.
21. Binbin Li, Ph.D. candidate, Dept. of Manufacturing Eng., Boston University.
22. D.J. Raghunathan, MS candidate (Completion Jan. 2002), Real Time Control over Data Networks with Constrained Communication Resources. Became PhD candidate July 1, 2005.

#### Harvard University

1. Hongyi Li, Ph.D. candidate
2. Abdol-Reza Mansouri, Ph.D. candidate
3. Michael McLeroy, Ph.D. candidate
4. Denjamin Pierce, Ph.D. candidate

#### University of Illinois

1. Arvind Giridhar, Ph.D. candidate
2. Binita Binita, PhD candidate
3. Robert A Rozovsky, PhD candidate
4. Yan Wu, PhD candidate
5. Vivek Raghunathan, PhD candidate
6. Craig Robinson, PhD candidate
7. Roberto Solis Robles, PhD candidate
8. Hemant Kowshik, PhD candidate
9. Min Cao, PhD candidate
10. Nikolaos Freris, PhD candidate
11. Kurt Plarre, PhD candidate
12. Feng Xue, PhD candidate
13. Adithya Yalavarti, PhD candidate
14. Kyoung-Dae Kim, PhD candidate

#### University of Maryland

1. P. Horvasheti, Ph.D. candidate.
2. Chang Zhang, Ph.D. candidate.
3. Lei Zhang, Ph.D. candidate.
4. A. Komaee, Ph.D. candidate.
5. K. Chakraborty, Ph.D. candidate.
6. D. Napoletani Ph.D. candidate.
7. Bijan Afsari (Ph.D. Applied Mathematics – expected to complete in May 2008)
8. Arash Komaee (Ph.D. Electrical Engineering – expected to complete in December 2007)
9. Kevin Galloway (Ph.D. Electrical Engineering – in progress)
10. Matteo Mischiati (Ph.D. Electrical Engineering – in progress) graduate fellow
11. Puduru Viswanadha Reddy (M.S. Electrical Engineering – expected to complete in May 2007).
12. Fumin Zhang Ph.D. awarded 2004. (Supported through other means but working on problems related to the



13. project).
14. Sean Andersson Ph.D. awarded 2003. (Supported through other means but working on problems related to
15. the project).
16. Cheng Shao, Ph.D. Candidate Zachary Reid Kulis (M.S. Electrical Engineering completed summer 2006)

## **M.S. Students**

### **Boston University:**

1. D.J. Raghunathan, MS candidate (Completion Jan. 2002), Real Time Control over Data Networks with Constrained Communication Resources
2. Atul A. Suri, MS candidate (Completion January, 2004), Information Patterns in Formation Control of Autonomous Vehicles
3. Hani M. Sallum, MS candidate, Department of Aerospace/Mechanical Engineering (Completion May, 2005), Development and Implementation of a High-Level Command System and Compact User Interface for Non-holonomic Robots.
4. Joshua Burnett, MS candidate, Department of Aerospace/Mechanical Engineering, Boston University.

### **University of Illinois**

1. Vikas Kawadia, MS candidate, (Completion December 2001).
2. Swetha Narayanaswamy, MS candidate, (Completion December 2001).

### **University of Maryland**

1. S. Klemm, MS candidate
2. Z. Kulis, MS candidate
3. M. Goldgeier, Undergraduate
4. M. Gebremichael, Undergraduate
5. P. Carlos Sodre, Undergraduate
6. T. Duong, Undergraduate
7. Adrian Cottin, Undergraduate
8. D. Luebke, Undergraduate
9. V. Shah, Undergraduate

## **7.1. Degrees Awarded**

### **Boston University**

1. D.J. Raghunathan, MS Degree, January 2002 Real Time Control over Data Networks with Constrained Communication Resources
2. Atul Asok Suri, MS Degree, January 2004, Information Patterns in Formation Control of Autonomous Vehicles
3. Ying Liu, "Analysis of Regulation Mechanisms in Communication Networks", M.S. in Manufacturing Engineering, Boston University, January 2003.



4. Yong Liu, "Pricing and Resource Allocation in Communication Networks and Supply Chains", Ph.D. in Systems Engineering, Boston University, May 2002.
5. S. Vassilaras, "Measurement-based Quality of Service Provisioning in Multimedia Telecommunication Networks", Ph.D. in Electrical and Computer Engineering, Boston University, January 2002.
6. Chang Su, "Target-pursuing policies for scheduling and routing in multiclass queueing networks", Ph.D. Systems Engineering, Boston University, May 2004.
7. Yimin Yu, "On transmission scheduling in wireless networks and route discovery for a fleet of robots", M.S. in Manufacturing Engineering, Boston University, September 2004.
8. Grace Kessenich, MS, Boston University, Department of Aerospace/Mechanical Engineering, May, 2005.
9. Hani Michael Sallum, MS, Boston University, Department of Aerospace/Mechanical Engineering, May, 2005.
10. Keyong Li, Boston University PhD, Department of Aerospace/Mechanical Engineering, January, 2006. Thesis title: "Robust and Efficient Feedback Coding for Communication-Based Control---Operating Under Data-Rate Constraints."
11. Wei Lai, "Optimizing Wireless Sensor Networks", Ph.D. in Systems Engineering, Boston University, January 2007.
12. Jian Shao, "Optimal Resource allocation in multi-class service systems using pricing", Ph.D. in Systems Engineering, Boston University, January 2005.
13. Yimin Yu, "On transmission scheduling in wireless networks and route discovery for a fleet of robots", M.S. in Manufacturing Engineering, Boston University, September 2004.

### **University of Illinois**

1. Vikas Kawadia, MS Degree, (Completion December 2001), Design and Implementation of a Power Control
2. Protocol in Ad-Hoc Networks.
3. Swetha Narayanaswamy, MS Degree, (Completion December 2001), Power Control in Ad-Hoc Wireless
4. Networks.
5. Scott R. Graham, PhD, July 8, 2004, Issues in the Convergence of Control with Communication and Computation
6. Ashish Agarwal, MS in Computer Science, May, 2004, The Capacity of Ad Hoc and Hybrid Wireless Networks under the Protocol and Physical Models,

### **Harvard University**

1. Aleksandar Rabiner, MS Degree, June 2002.
2. Abdul Reza Mansouri, PhD candidate --graduated June 2004. Thesis title is "Sub-Elliptic Diffusions, Geometry, and Control"
3. Hongy Li-PhD candidate-graduated June 2004. Thesis title is "Choreographing Dynamical Systems"

### **University of Maryland**

1. Sean Andersson, Ph.D (August 2003). Thesis: Geometric Phases in Sensing and Control.
2. Phillip Yip, "Symbol-based control of a ball-on-plate mechanical system", M.S. Thesis, University of Maryland, College Park, 2004. Degree awarded June 2004. (The student was associated with the MURI project, but his funding came from a leveraged source.)



3. Bijan Afsari (May 2004), M.S. in Electrical and Computer Engineering.
4. Fumin Zhang Ph.D. Ph.D University of Maryland, (December 2004), "Geometric Cooperative Control of Robot Formations."
5. Wei Xi, PhD PhD in Electrical and Computer Engineering, University of Maryland College Park, December 2006. Thesis Title: *Control of Autonomous Swarms Under Communication and Resource Constraints*.
6. Maben Rabi, PhD in Electrical and Computer Engineering, University of Maryland College Park, December 2006. Thesis Title: *Packet Based Inference and Control* .

## **8. Patents and Inventions**

M. A. Vorontsov, E. W. Justh, L. Beresnev, P. S. Krishnaprasad and J. C. Ricklin (2005), "Wavefront Phase Sensors Based using Optically or Electrically Controlled Phase Spatial Light Modulators" (2002), Joint disclosure to the University of Maryland and Army Research Laboratory (PS-2001-078). Awarded U.S. Patent 6,911,637 in 2005 (with M. A. Vorontsov, E. W. Justh, L. Beresnev, J. C. Ricklin)

T.G. Bifano, 2003 U.S. Patent (#6,529,311) MEMS-based Spatial-light Modulator



## Appendix 1. Technology Transfer

At Boston University Paschalidis has spearheaded the creation of the Sensor Network Consortium (SNC) and serves as the SNC Academic Director. SNC aims at bringing together industry and academia to drive research and development, facilitate technology transfer, and influence the future development of the sensor networking industry. Currently, SNC industrial members include ArchRock, BP Int'l, Crossbow Inc., Ember Corp, Honeywell Corp, IBM, Millennial Net, Mitre Corp, SAP, Siemens, Sun Microsystems, Textron Systems, and The Hartford Financial Services Group, Inc. (See also <http://www.bu.edu/snc>.) Several of these companies have strong experience in military sensor platforms (e.g., OASIS by Textron, etc.) and are benefiting from the sensor networking work done at Boston University. As a direct result of contacts established through the SNC, principals of the Center for Communicating Networked Control Systems participated in (and help organize) a workshop on sensor networks held over two days --- March 9, 10, 2006 --- at the Los Alamos National Laboratory. A related (but technically distinct) day-long workshop was held at the MITRE Corporation in Bedford, MA.

Following discussions with Dr. Jeff Heyer and collaborators at the Naval Research Laboratory (NRL), significant progress has been made in the area of cooperative control of unmanned aerial vehicles. Initial demonstrations of algorithms and control architectures using ground vehicles have been carried out. Steps are being taken to transition this work to air vehicles, as well as autonomous sea surface vehicles. A key intermediate step is to test our ideas in a hardware-in-the loop autopilot test-bed. **Piccolo** autopilots have been chosen by the NRL group. One of these is now available in the Intelligent Servosystems Laboratory (ISL) to facilitate software development via simulation studies. Current plans include transition of cooperative control algorithms developed in the MURI project and software to the **Dragoneye** platform. Issues regarding communication links between vehicles, based on ultra-wide-band (UWB) radio, and coupled GPS-UWB ranging will be investigated in this joint effort. Kevin Galloway carried out a complete demonstration at NRL of the Justh-Krishnaprasad algorithms for cooperative control of three UAV's in a hardware-in-the-loop test-bed using Piccolo autopilots during summer 2005. He continued this work in summer 2006, while doing reserve officer duty at NRL. The aircraft dynamics models he employed were pertinent to the Dragoneye platform. As a reserve officer in the Navy, Galloway continued to work periodically at NRL during the course of fall 2006. In fall 2006, he has been a full time research assistant developing the MURI research results on the use of the Cricket beacon network for localization and control of groups of robots. A new student from Italy, Matteo Mischiati, supported by a graduate fellowship, has joined the team in ISL during fall 2006. He has extensive industrial experience with a helicopter manufacturer in a Italy.

A hovercraft platform has been developed in ISL to explore control under limited communication over a Bluetooth link. This platform exploits ultrasonics to localize accurately within the lab. This "indoor GPS system" is derived from a commercial realization (from Crossbow Technologies) of the Cricket system developed at MIT. A set of "motes" equipped with radio frequency transceivers and ultrasonic transceivers has been installed in the lab. The mobile (hovercraft) uses ultrasonic time of flight measurements to determine its location to within a few centimeters in the lab. This system was replicated during summer 2006 and fall 2006 on multiple vehicles to provide a means to test within the lab formation control laws. Extensive software and hardware experience has been gained in the process and will be shared with ARL researchers and engineers.

Undergraduate engineers trained in ISL have become strongly involved in projects closely related to the MURI theme at organizations where they have taken up temporary or permanent employment (NRL, Northrop Grumman, General Dynamics, Intelligent Automation Inc.). The work with IAI is leading to transition of many ideas and technologies developed with MURI support. As an employee of IAI, Zachary Kulis (who defended his M.S. thesis in May 2006 on hovercraft control under Cricket) has been a critical link for technology transfer. He continues to interact with the MURI team in Maryland.

IAI has initiated a formal internship program with the Intelligent Servosystems Laboratory (ISL) and it is expected that two students affiliated to the lab will be on site at IAI for the summer of 2007. IAI has also provided free access to Cybele a distributed computation framework for modeling and analysis of agent



systems in ISL. An agent-based open source version of MDLe is being prepared at IAI and is also expected to be available in ISL to continue our research.

At Boston University there is a longstanding and ongoing collaboration with Dr. Mikhail Vorontsov and others at the ARL Intelligent Optics Laboratory. Joint work between the Vorontsov group and the Boston University Precision Optics Laboratory has resulted in eight collaborative papers in archival journals and conference proceedings and four specially-organized technical conference sessions at annual meetings of the Society of Photo-optical Instrumentation Engineers (SPIE) on the topic of high resolution wavefront control.

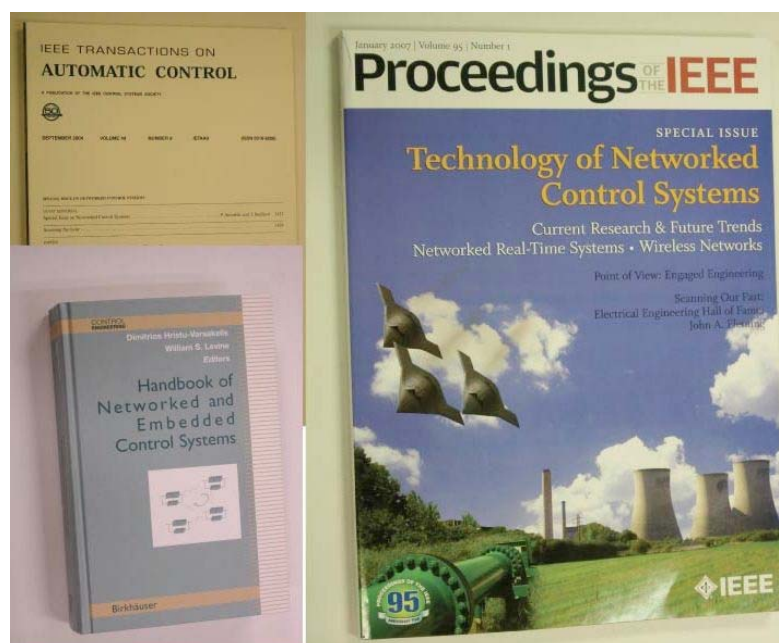
We have begun discussions with people at the Army's Weapons Technology Analysis Branch at the Aberdeen Proving Grounds on possible interactions/collaborations on human operator interfaces for groups of mobile robots. Dr. Stephen "Drew" Wilkerson visited Boston University in February, and a return visit by Center personnel took place on May 18. Participating in the visit were project PI's Baillieul, Bifano, Justh, Krishnaprasad, and Paschalidis. following this some initial steps were taken towards establishing a CRADA. It is anticipated that further work will lead to possible use of acoustic sensors on UAVs to detect and localize explosions.

This past spring, Boston University---with participation from investigators Baillieul and Paschalidis---hosted a two-day NSF Workshop on May 25-26, 2006: *Future Directions in Systems Research for Networked Sensing*.

At the University of Maryland, there is an NSF grant that supports a laboratory course on networked and embedded control systems. This has resulted in the "Handbook for Networked and Embedded Control Systems", to be published by Birkhauser in 2005. This is jointly edited by Center P.I. D. Hristu-Varsakelis and W. Levine.

Team members have continued interacting with researchers from Telcordia, Johns Hopkins APL, BBN, and Boeing FCS, in an effort to further develop the application of our dynamic clustering methods using value-function non-variation in autoconfiguration and routing.

With University of Notre Dame colleague Panos Antsaklis, CNCS MURI P.I. John Baillieul has guest edited special issues of the *IEEE Transactions on Automatic Control* (September, 2004) and the *Proceedings of the IEEE* (January, 2007) concerned with networked control systems. A number of members of the project team (Hristu-Varsakelis, Baillieul, Raghunathan, and Suri) were involved in the publication of the Birkhauser volume entitled the *Handbook of Networked and Embedded Control Systems*.





## Appendix 2. Awards and Recognitions

1. John Baillieul - Became 40-th President of the IEEE Control Systems Society, for 2006.
2. John Baillieul was appointed Editor-in-Chief of the *SIAM J. on Control and Optimization* (SICON).
3. Roger Brockett was awarded the ASME's Rufus Oldenburger Medal in November of 2005.
4. John S. Baras was named corresponding member of the Swedish Academy of Sciences.
5. P.S. Krishnaprasad will receive the IEEE Control Systems Society Bode Prize and deliver the annual Bode Lecture at the Conference on Decision and Control in December, 2007.